SOLENOID BASED RING COOLERS

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Attractive features of a ring cooler are:

1. Multiple using of all parts including acceleration, absorbers, etc.
2. The most natural and relatively easy emittance exchange for a longitudinal cooling.

Two kinds of the ring coolers are considered:

1. High RF rings for 6D cooling ('cooler').
2. Low RF rings mainly for longitudinal cooling ('bunch compressor').

1st can be considered as a less expansive (if so!) alternative to linear coolers.

2nd provides longitudinal cooling factor 10-20 and has no alternatives at present. Strong longitudinal cooling is required for production of short high intensity bunches for a muon collider.

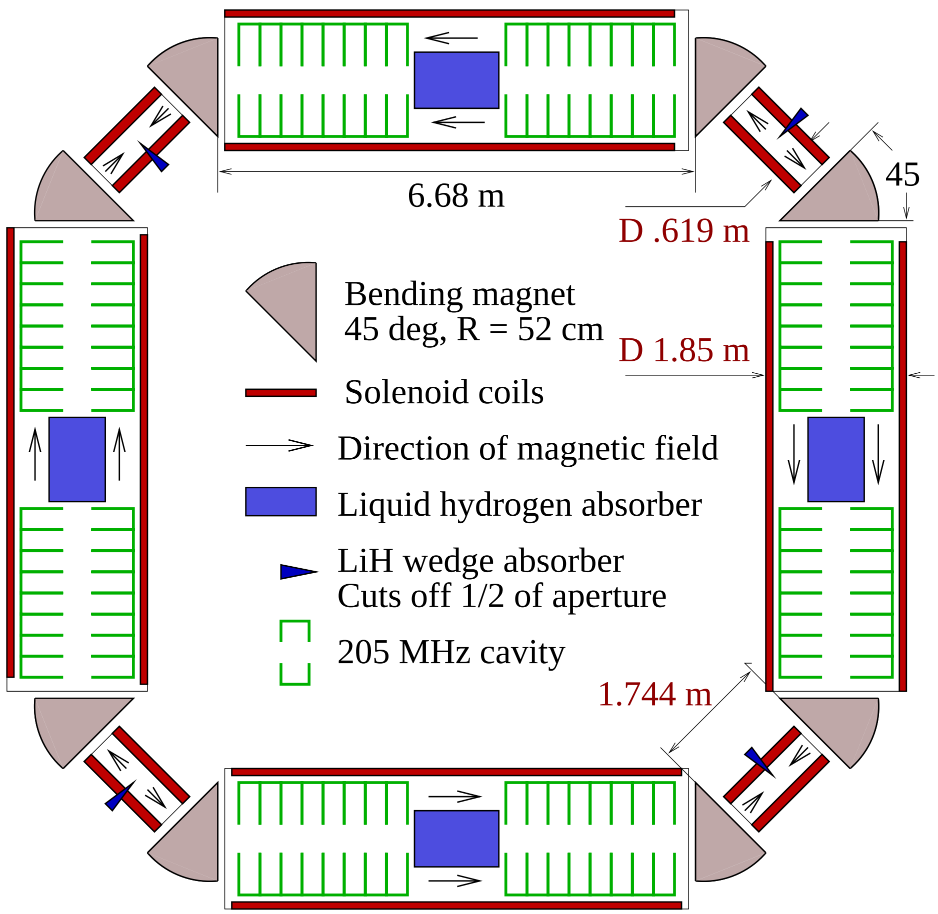
Transverse focusing by alternate solenoids is considered in all the cases. Motivation is the same as for linear coolers.

Hard edges approximation on the boundary between dipoles and solenoids is used.

High RF Cooler

Outline

1. Layout and parameters.
2. Coils and field.
3. Dispersion and beta-function.
4. Performances.

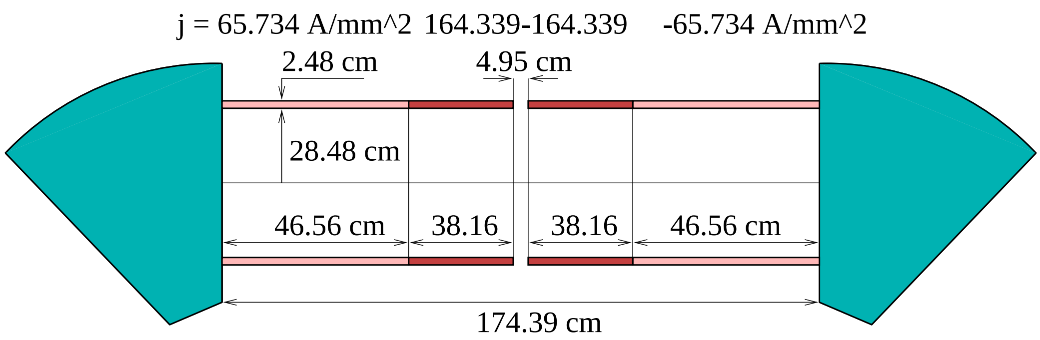


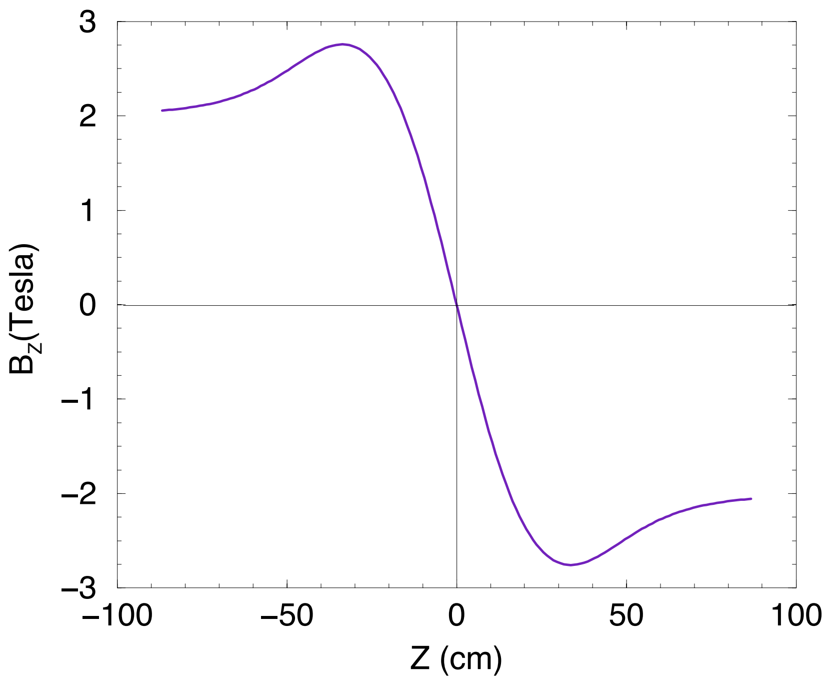
Layout of the ring cooler.

Table of parameters

Circumference	36.963 m
Reference energy before/after absorber	269.2/230.8 MeV
Number of bending magnets	8
Bending angle	45°
Bending radius	52 cm
Bending field	1.453 T
Normalized field gradient	0.5
Length of short SS	1.7439 m
Length of long SS	6.680 m
Maximal axial field of solenoid	5.155 T
Revolution frequency	7.34606 MHz
RF harmonic number	28
RF frequency	205.690 MHz
Accelerating gradient	15 MeV/m
LH_2 main absorber, length	128.1 cm
14 cm LiH wedge absorber, dE/dy	0.75 MeV/cm

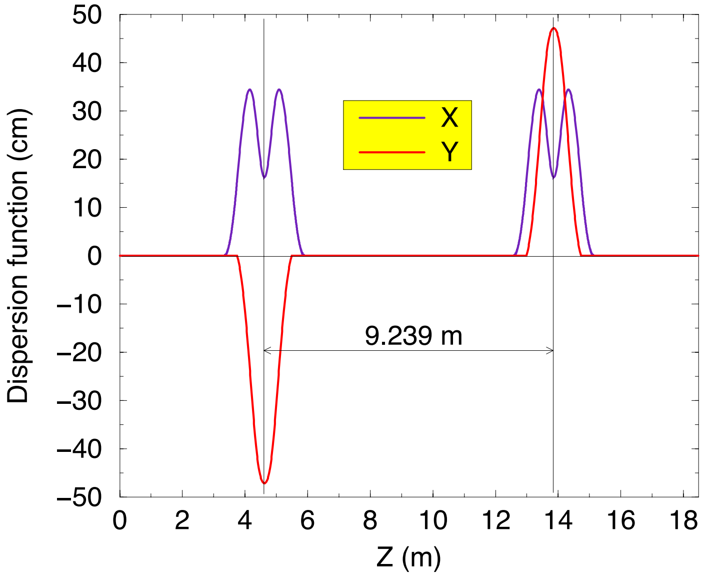
Short straight section



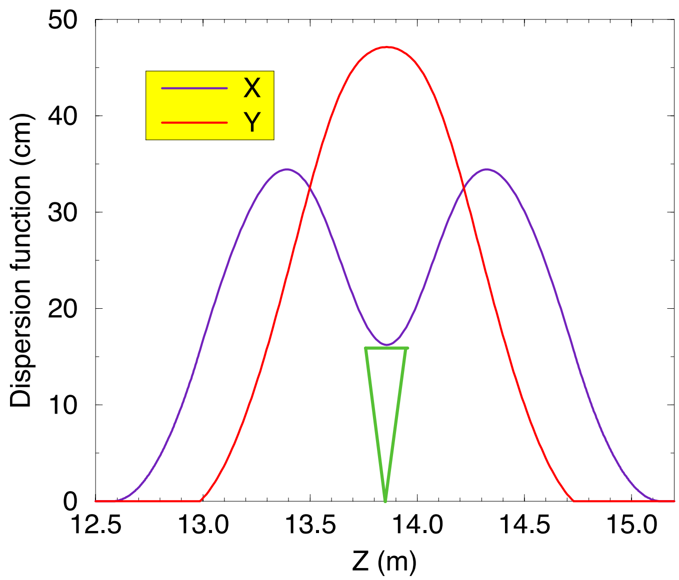


Layout and axial magnetic field of the short straight section. Linear dispersion $\neq 0$ only in this part. Symmetric field flip provides conservation of angular momentum.

Linear dispersion

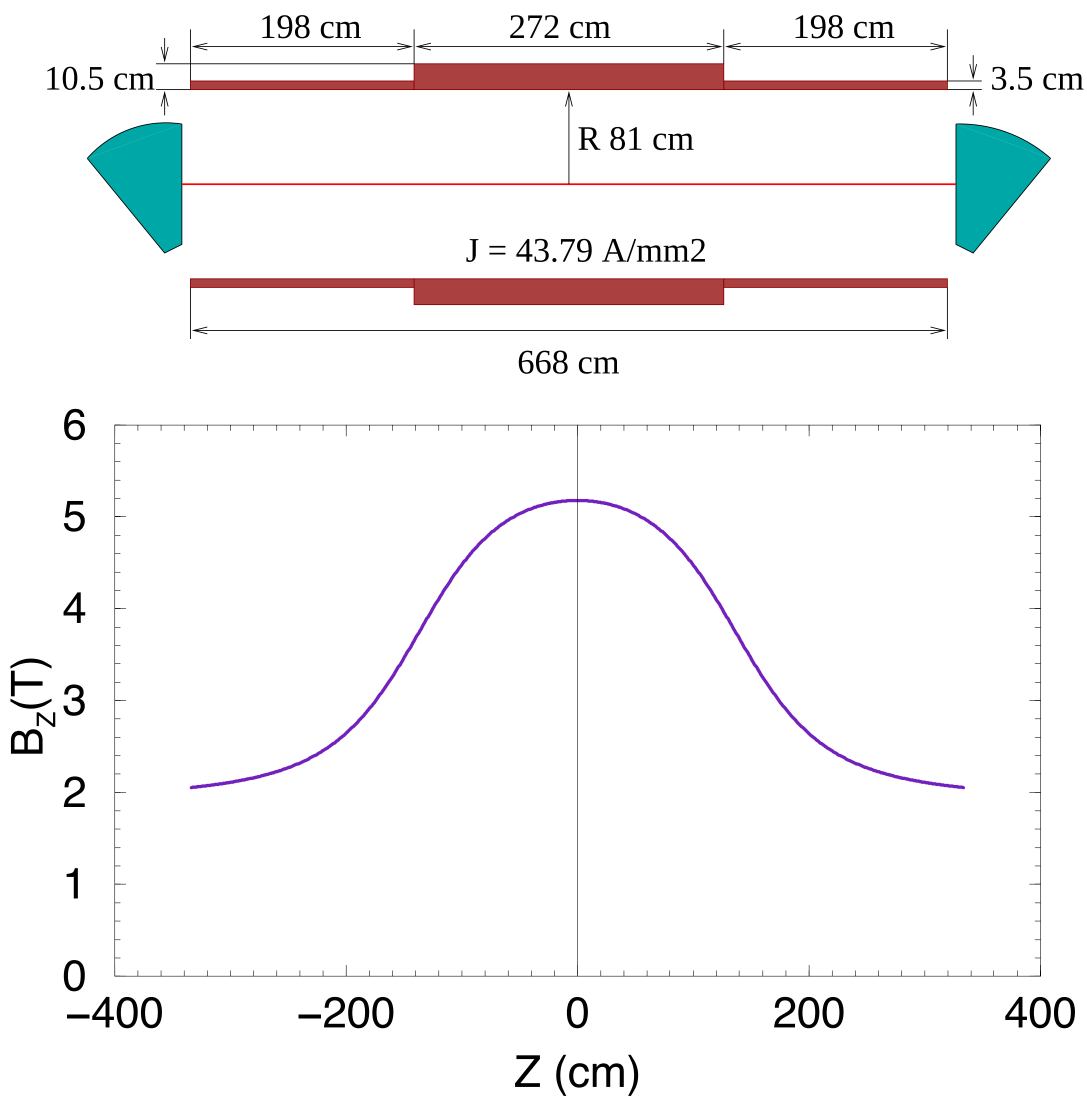


Dispersion function at 1/2 of the ring.



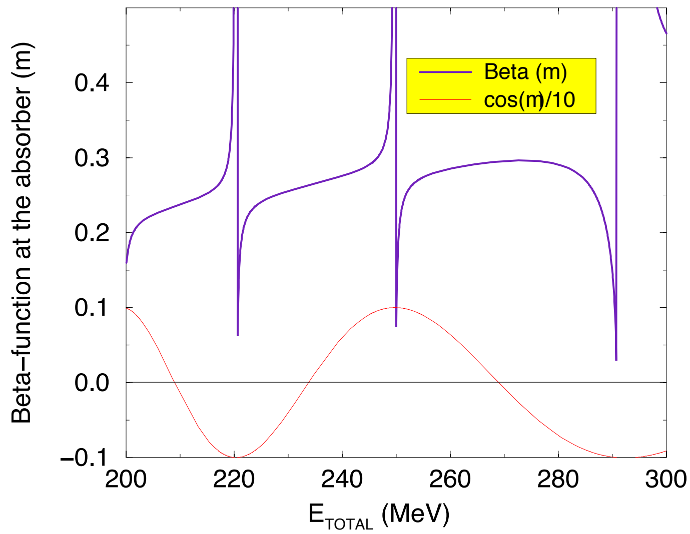
Dispersion function and wedge absorber.

Long straight section

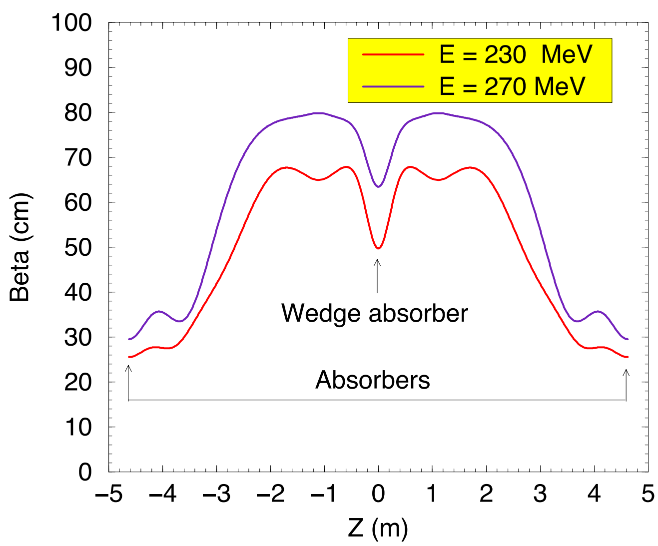


Layout and axial magnetic field of the long SS. Adiabatic increase of the field provides low beta at the absorber.

Beta-function

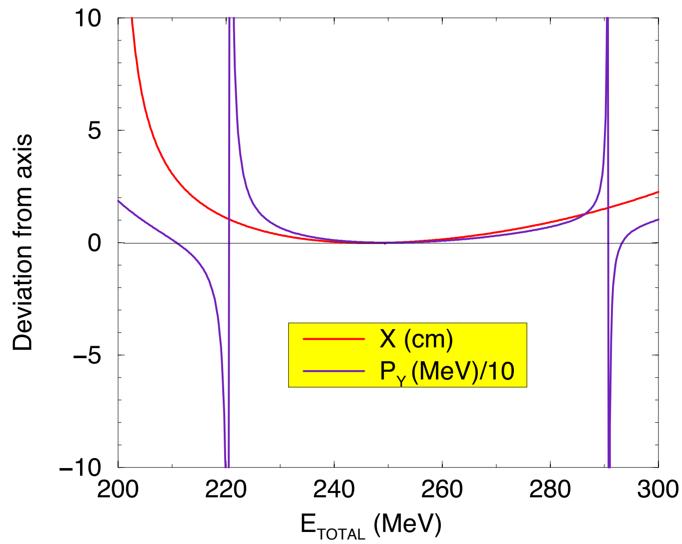


Beta-function at the absorber vs energy. Systematic non-linearity of magnetic field of dipoles stabilizes these resonances.

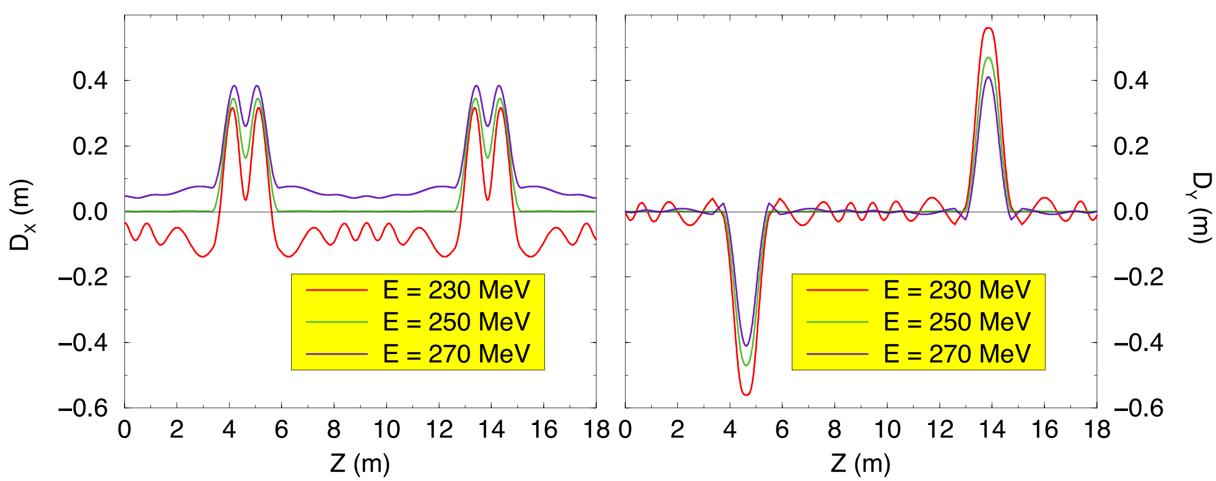


Beta-function vs distance. It is 25-30 cm at the absorbers corresponding to transverse equilibrium emittance 1.2-1.5 mm **without emittance exchange**.

Nonlinear dispersion



Deviation of closed orbit at the absorber vs energy. Stabilization by nonlinearity is unclear.

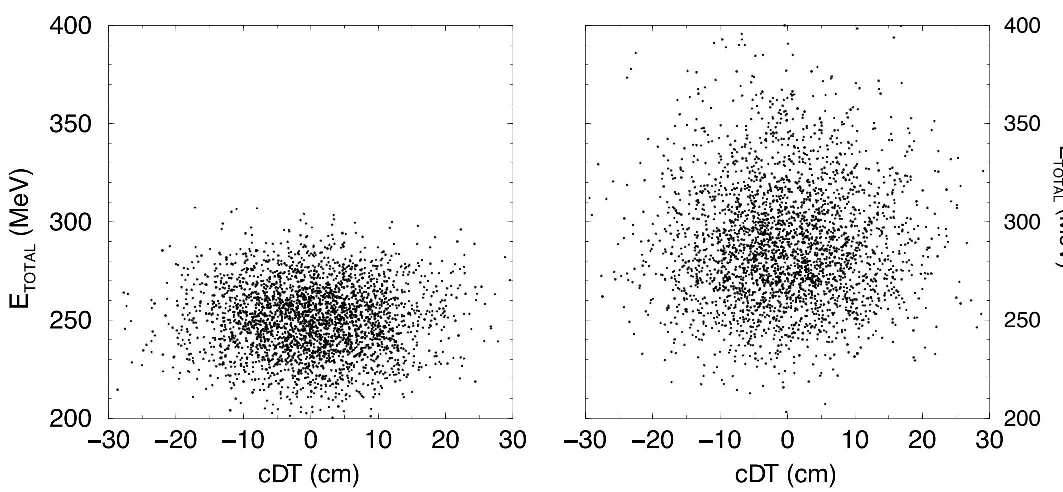


Dispersion function vs distance. Nonzero dispersion in the long SS + dependence of revolution frequency on energy produce parametric excitation of synchrotron oscillations.

Simulation: parameters of injected beam

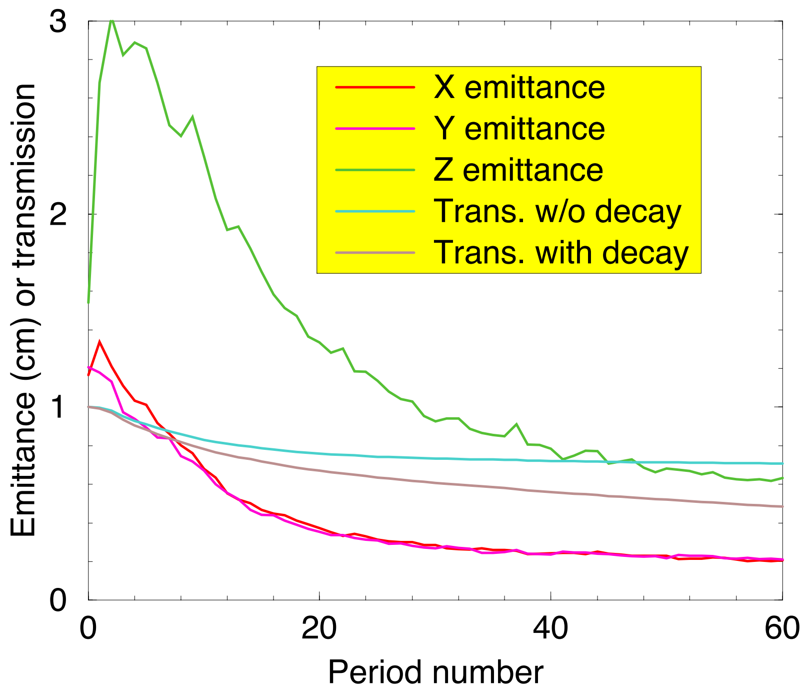
- Injection point – center of long SS
- 6D Gaussian distribution, 3000 muons
- R.m.s. beam size:
  $\sigma_X = \sigma_Y = 4$ cm
  $\sigma_{P_x} = \sigma_{P_y} = 32$ MeV/c
  $\sigma_{cT} = 9$ cm
  $\sigma_E = 18$ MeV
- Normalized emittance:
  $\varepsilon_X = \varepsilon_Y = 1.2$ cm
  $\varepsilon_Z = 1.5$ cm
- Energy - momentum correlation:

$$E = E_{ref}\sqrt{1 + \Big[\Big(\frac{p_t}{mc}\Big)^2 + \Big(\frac{eB_{absor}r}{2mc^2}\Big)^2\Big]_{random}} + \Delta E_{random}$$



Longitudinal phase space at injection. Left/right – without/with energy-momentum correlations.

Simulation: evolution of r.m.s. emittances



Number of turns	0	5	10	15
X-emittance (cm)	1.2	0.37	0.24	0.21
Y-emittance (cm)	1.2	0.35	0.24	0.21
Z-emittance (cm)	1.5	1.3	0.79	0.63
6D-emittance (cm^3)	2.2	0.18	0.045	0.028
Transmission without decay	1	0.76	0.72	0.71
Transmission with decay	1	0.67	0.56	0.48
Merit factor ($Tr \times \varepsilon_{6,ini}/\varepsilon_{6,fin}$)	1	8.2	27	38

Conclusion: Transverse emittance at the ring cooler is about the same as at SFOFO channel. Longitudinal emittance is noticeable less. Realistic injection scheme should be considered for comparison of the performances.

Bunch Compression

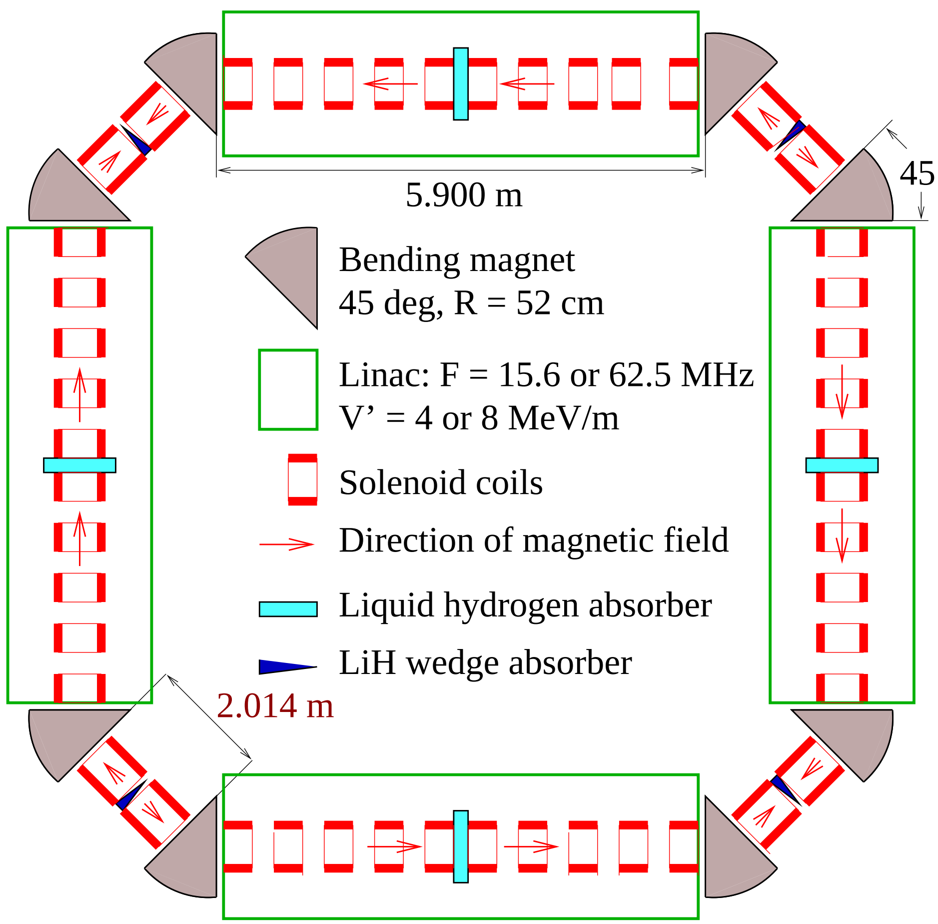
- **Optimal regime for muon collider:** Single bunch at proton driver ⇒ single bunch at the collider.
- **After phase rotation:** Length of muon bunch is at least 6-8 m (RF rotation).
- **For 200 MHz cooler:** Length of the bunch should be 0.6-0.8 m (about 10 cm r.m.s.).
- **Strong emittance exchange** is needed for similar bunch compression.
- **Low RF ring cooler is suitable for this.**

- **The cooler as above with low RF (8 MHz, 3 MeV/m) was considered firstly.** Very low transmission.
- **Improvement:** Uniform field at the long SS (transverse cooling is not the goal in this case!). Transmission about 30%, final longitudinal emittance about 10 cm (required 2-3 cm).
- **The same at paraxial approximation:** Transmission is 54% (100% without decay), longitudinal emittance 1.6 cm (http://www.physics.ucla.edu/snowmass).
- **Main reasons of the degradations:**

1. Dependence of revolution frequency on transverse momentum.
2. Nonzero dispersion at long straight sections.
3. Low cooling rate (low accelerating gradient).

Two-Steps Bunch Compressor

Step by step increase of RF and accelerating gradient ($V \propto \sqrt{F}$) gives a chance to get more cooling rate and longitudinal cooling factor.

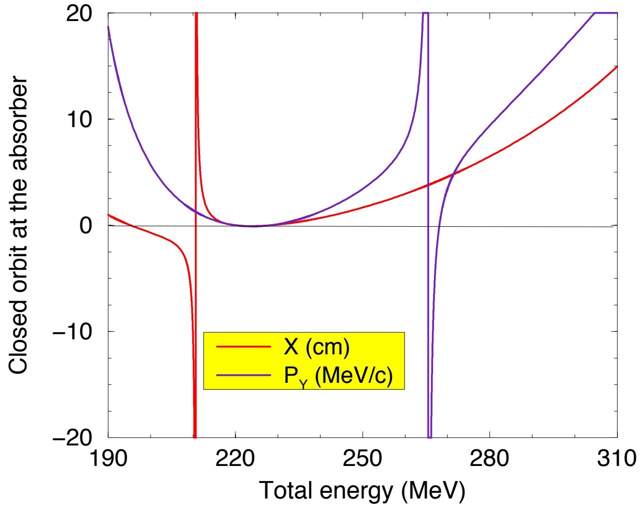


Layout of the ring cooler – bunch compressor. Magnetic field at the long SS is 1.751 T

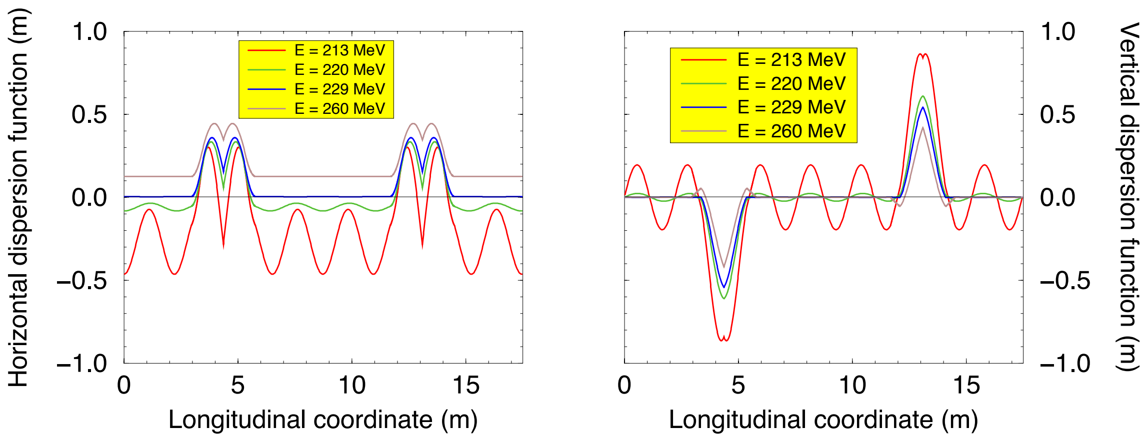
Table of Parameters

Parameter	1st compr.	2nd
Circumference	34.921 m	same
Nominal energy (total)	220 MeV	same
Number of bending magnets	8	same
Bending angle	45°	same
Bending radius	52 cm	same
Bending field	1.238 T	same
Normalized field gradient	0.5	same
Length of short SS	2.104 m	same
Length of long SS	5.900 m	same
Axial field of the long solenoid	1.751 T	same
Beta function at nominal energy	0.735 m	same
Synchronous phase	30°	same
Revolution frequency	7.530 MHz	same
Accelerating frequency	15.065 MHz	60.24
RF harmonic number	2	8
Accelerating gradient	4 MeV/m	8
LH_2 main absorber, length	35.9 cm	71.7
LiH wedge absorber, dE/dy at $y > 0$ (0 at $y < 0$)	0.14 MeV/cm	0.30

Nonlinear dispersion



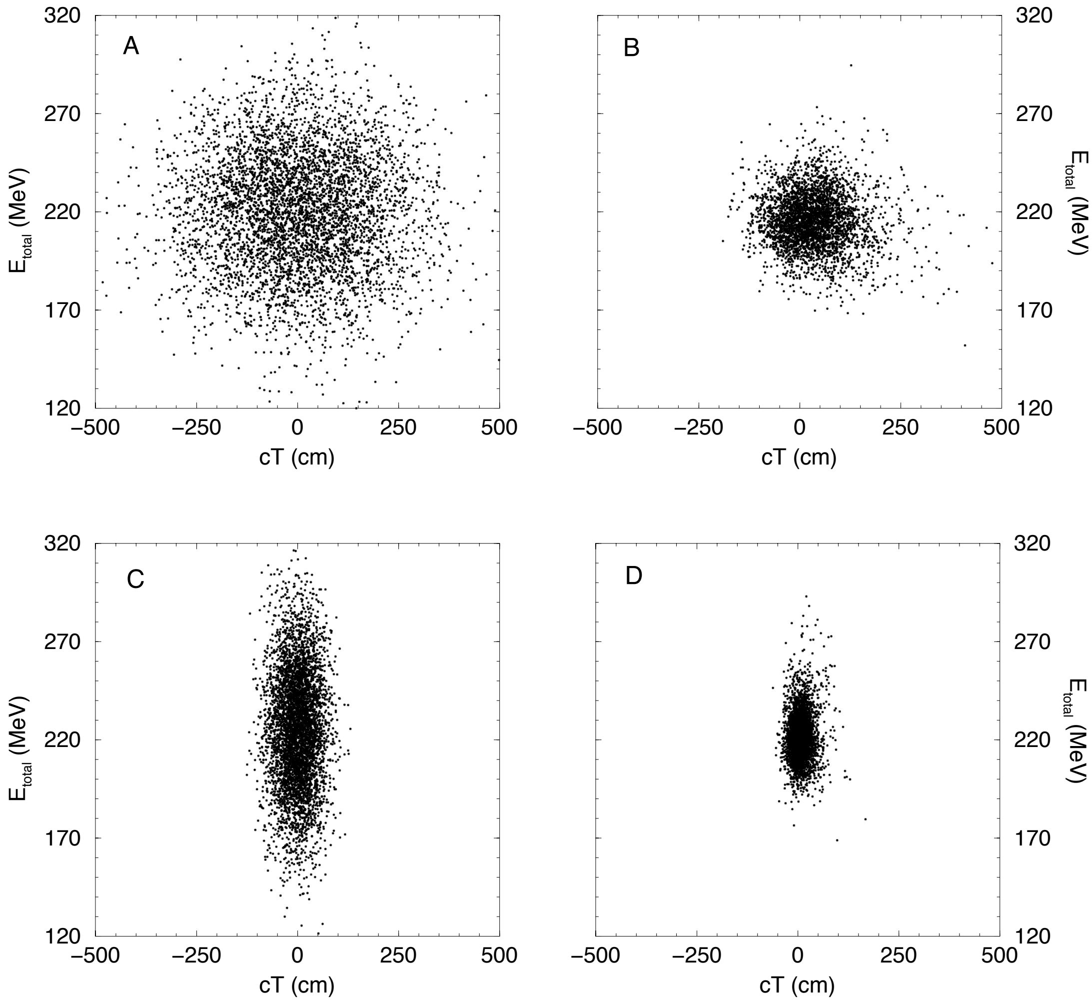
Dependence of dispersion on energy at the center of long SS. $Y = P_x = 0$ here.



Dispersion function vs Z at various energy.

- Nonzero dispersion → oscillation of transverse momentum with synchrotron frequency.
- \+ Dependence of revolution frequency on transverse momentum → parametric perturbation: oscillation of the revolution frequency with double synchrotron frequency.

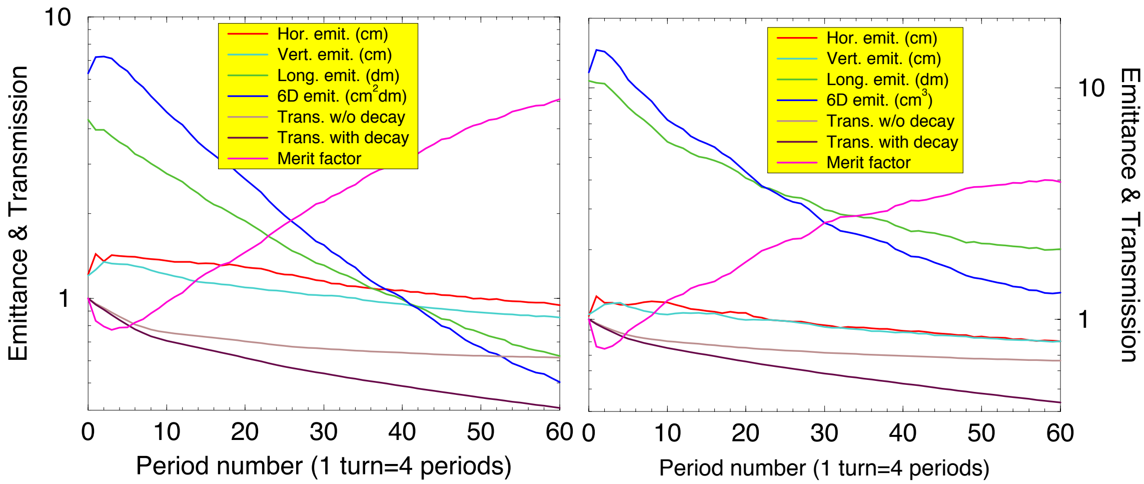
Longitudinal phase space at the cooling



Longitudinal phase space:

A – at injection to the 1st compressor;
B – after 10 turns in the 1st compressor;
C – at injection to the 2nd compressor;
D – after 10 turns in the 2nd compressor.

Cooling simulation



Evolution of emittances: left/right – 1st/2nd stages.

Parameter	Begin.	C1	C2
Horizontal emittance (cm)	1.2	1.0	0.88
Vertical emittance (cm)	1.2	1.0	0.88
Longitudinal emittance (cm)	43	10	2.5
6D emittance (cm^3)	63	10	2.0
Transmission without decay	1	0.64	0.70
Transmission with decay	1	0.49	0.53
Merit factor ($Tr \times \varepsilon_{6,ini}/\varepsilon_{6,fin}$)	1	3.1	3.2
Accumulated transmission	1	0.49	0.26
Accumulated merit factor	1	3.1	10

Conclusion: Two steps low RF ring coolers can provide longitudinal bunch compression as required for muon collider.

Octagonal Ring Cooler – Bunch Compressor

• Decrease of parasitic dispersion at long SS weakens the perturbations of synchrotron oscillations.
• It can be reached by using of less angle bending magnets.
• Decrease of dispersion function at the short SS should be compensated by thicker wedge absorbers.

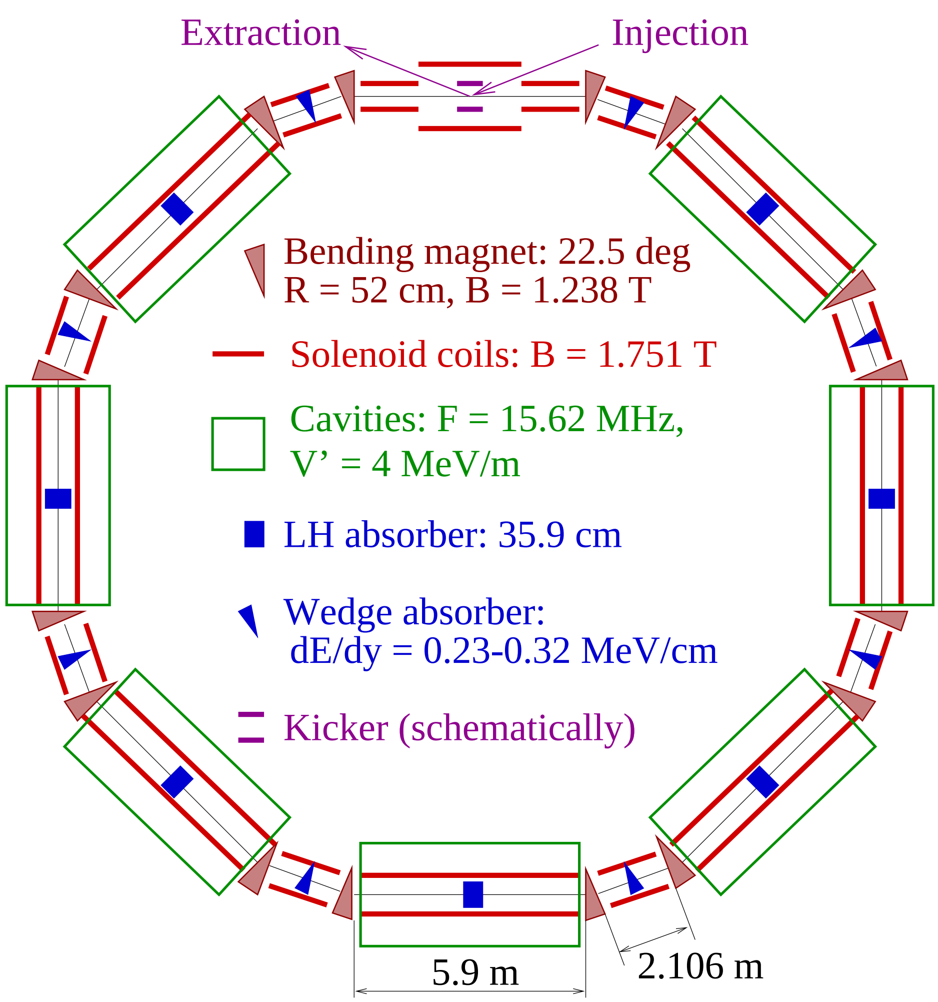
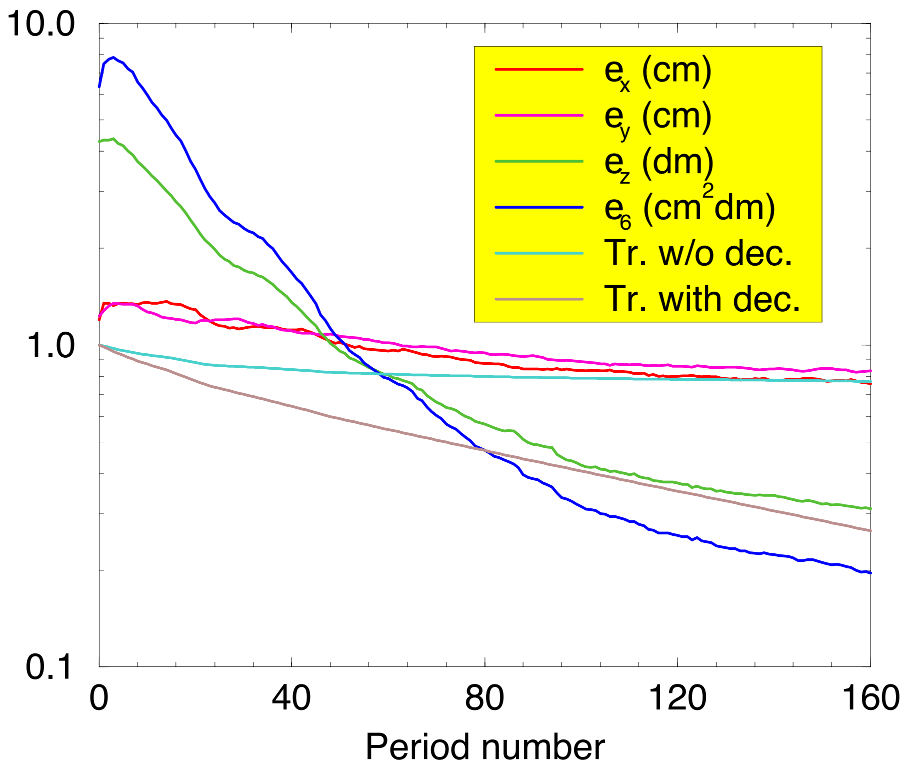


Table of Parameters

Parameter	
Circumference	67.317 m
Nominal energy (total)	220 MeV
Number of bending magnets	16
Bending angle	22.5°
Bending radius	52 cm
Bending field	1.238 T
Normalized field gradient	0.5
Length of short SS	2.106 m
Length of long SS	5.900 m
Axial field of the long solenoid	1.751 T
Beta function at nominal energy	0.735 m
Synchronous phase	30°
Revolution frequency	3.906
Accelerating frequency	15.624MHz
RF harmonic number	4
Accelerating gradient	4 MeV/m
LH_2 main absorber, length	35.9 cm
LiH wedge absorber, dE/dy	0.23-0.32 MeV/cm

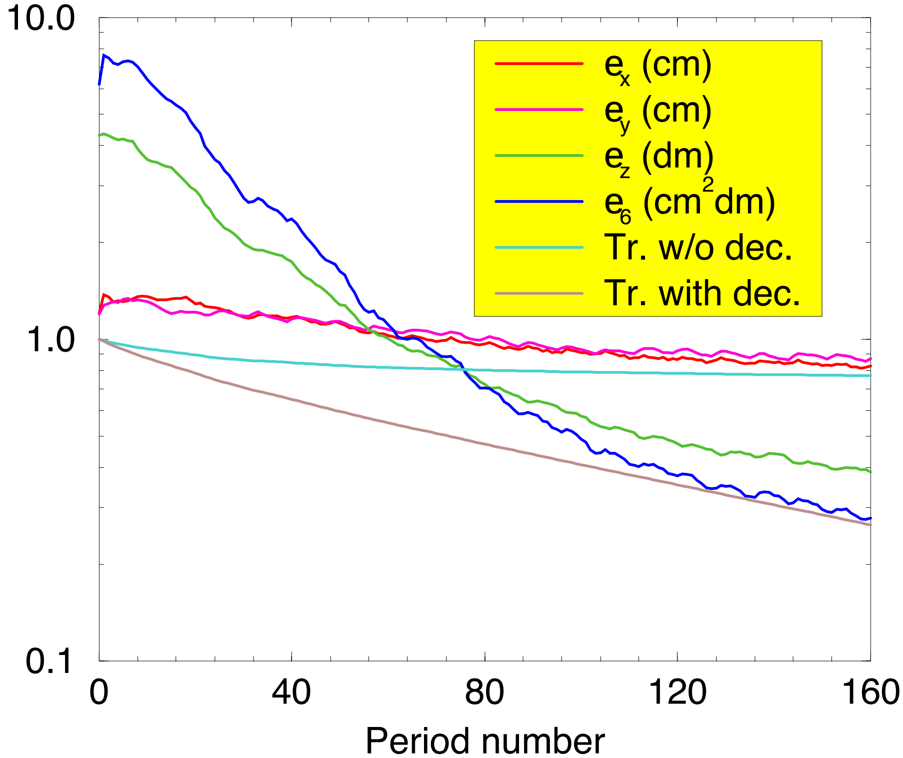
Simulation: RF at all long SS, LiH wedge absorbers 0.32 MeV/cm; 10 Kmuons



Number of turns	0	5	10	15	20
Horizontal emittance (cm)	1.2	1.1	0.88	0.80	0.76
Vertical emittance (cm)	1.2	1.1	0.95	0.86	0.83
Longitudinal emittance (cm)	43	14	5.7	3.7	3.1
6D emittance (cm^3)	63	17	4.7	2.6	2.0
Transmission without decay	1	0.84	0.80	0.78	0.77
Transmission with decay	1	0.65	0.47	0.35	0.26
Merit factor ($Tr \times \varepsilon_{6,ini}/\varepsilon_{6,fin}$)	1	2.4	6.3	8.7	8.6

Very close to two steps compressor.

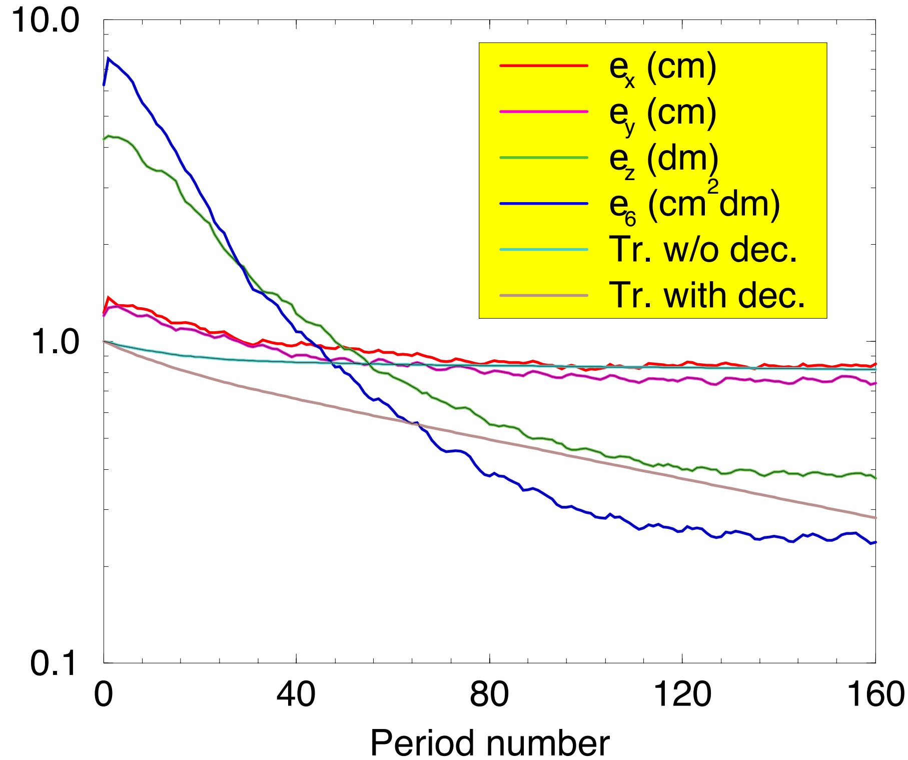
Simulation: RF at 7 long SS, LiH wedge absorbers 0.28 MeV/cm; 10 Kmuons



Number of turns	0	5	10	15	20
Horizontal emittance (cm)	1.2	1.2	0.97	0.86	0.83
Vertical emittance (cm)	1.2	1.2	1.0	0.92	0.87
Longitudinal emittance (cm)	43	17	7.2	4.7	3.9
6D emittance (cm^3)	62	23	7.1	3.8	2.8
Transmission without decay	1	0.85	0.80	0.78	0.77
Transmission with decay	1	0.65	0.47	0.35	0.27
Merit factor ($Tr \times \varepsilon_{6,ini}/\varepsilon_{6,fin}$)	1	1.7	4.2	5.9	5.9

Both decrease of average accelerating gradient and violation of symmetry make worse performances.

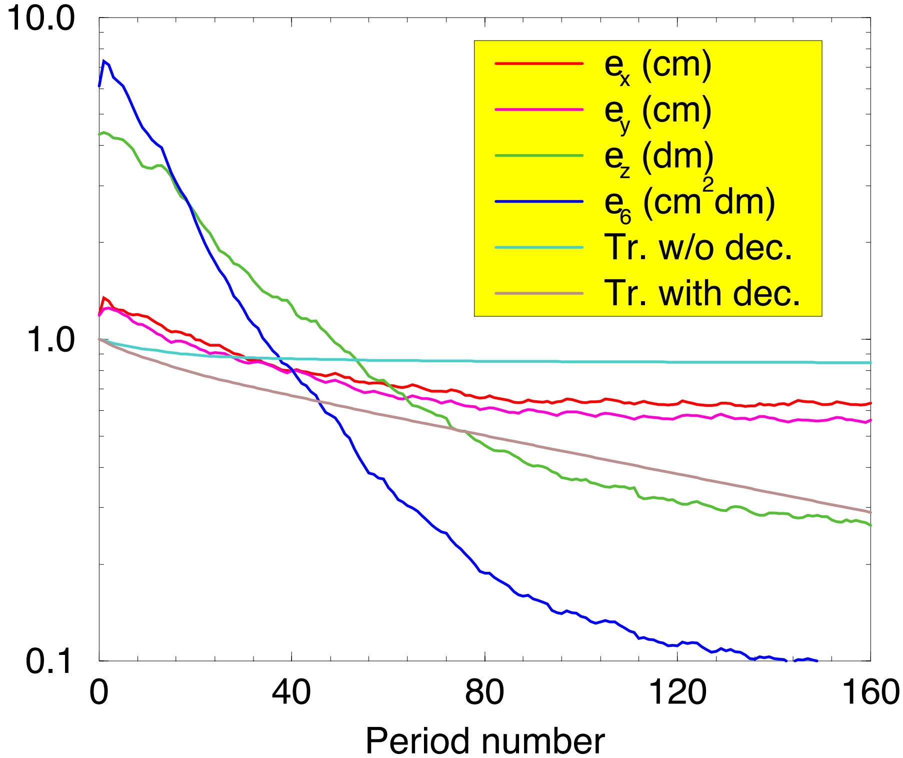
RF at 7 long SS and all short SS, LiH wedge absorbers 0.23 MeV/cm; 10 Kmuons



Number of turns	0	5	10	15	20
Horizontal emittance (cm)	1.2	0.97	0.86	0.85	0.85
Vertical emittance (cm)	1.2	0.91	0.80	0.76	0.74
Longitudinal emittance (cm)	43	12	5.1	4.0	3.8
6D emittance (cm^3)	63	11	3.8	2.6	2.4
Transmission without decay	1	0.86	0.84	0.83	0.82
Transmission with decay	1	0.66	0.50	0.37	0.28
Merit factor($Tr \times \varepsilon_{6,ini}/\varepsilon_{6,fin}$)	1	3.9	8.1	9.1	7.5

Both increase of average accelerating gradient and more linear energy loss in the wedge absorber improve the performances.

RF at 7 long SS and all short SS, LH_2 wedge absorbers 0.23 MeV/cm; 10 Kmuons



Number of turns	0	5	10	15	20
Horizontal emittance (cm)	1.2	0.80	0.66	0.63	0.63
Vertical emittance (cm)	1.2	0.80	0.61	0.57	0.56
Longitudinal emittance (cm)	43	13	4.7	3.1	2.6
6D emittance (cm^3)	61	8.1	1.9	1.1	0.94
Transmission without decay	1	0.87	0.85	0.85	0.85
Transmission with decay	1	0.67	0.51	0.38	0.30
Merit factor ($Tr \times \varepsilon_{6,ini}/\varepsilon_{6,fin}$)	1	5.1	16	21	19

Unexpectedly strong effect of scattering at the wedge absorbers.

Conclusion: Symmetrical octagonal bunch compressor has about the same performances as the two steps tetragonal compressor. Problem of injection looks easier.

Summary

• Cooling by a ring can be used both for 6D cooling ('cooler') and specially for a strong longitudinal cooling ('bunch compressor').

• The ring cooler with 5 T solenoids has approximately the same performances as SFOFO linear cooling channel.

• Two options of a bunch compressor are considered: 2×35 m and 1×67 m. Using 1.75 T solenoids, both of them can provide longitudinal bunch compression as required for muon collider.

• Nonlinear perturbations of longitudinal motion looks as the most serious physical problem. Decrease of dispersion weakens this effect.

• Injection is the crucial point of a cooling ring. It looks easier for the longer bunch compressor.

• Another important problem is calculation of 3D magnetic field of dipoles and an additional optimization of the cooler beyond the frame of hard edges approximation.